Beyond the Standard Model

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Abstract

A few topics beyond the standard model are reviewed.

1. INTRODUCTION

The subject of physics beyond the Standard Model (SM) began flourishing around the year 1978. In early 1978 SLAC discovered parity violation in neutral processes. That convinced many ambitious theorists that the SM was correct and they started to focus on the next layer of fundamental questions. At this point a dichotomy started emerging between theory and experiment. Theorists began focusing on speculative ideas. These came in basically four categories:

- Unification [1,2];
- Technicolor [3];
- Supersymmetric (SUSY) Unification [4,5];
- Superstrings [6].

and they concentrated mostly on the blemishes of the SM and on reasons why it cannot be a fundamental theory. On the other hand our experimentalist friends have been confirming the SM year after year. $W^{\pm}$ Z^0 have been discovered at CERN [7,8] and the top at Fermilab [9] and high level precision electroweak tests by LEP [10] have been vindicating the SM over and over again. So, to first approximation it is fair to say that there is no need to go beyond the SM and that therefore this talk is unnecessary.

This is indeed the situation to first approximation, except for a small, but perhaps significant, hint that has emerged recently. This hint comes from the weak mixing angle measured by the LEP experiments [11] and

SLD [12]. Supersymmetric unified theories that were proposed in 1981 [4,5] predicted the weak mixing angle, $\sin^2 \theta_W$ to within a theoretical uncertainty of approximately ±1%. Recent experimental measurements have measured this angle to roughly ±0.2%. The theoretical prediction agrees very well with experiment. Now of course this could just be a coincidence; the *a priori* probability for this is 2%. If you adopt the viewpoint that this is just a coincidence then you really have no hint of physics beyond the SM. We will adopt a different viewpoint, we will take this coincidence seriously and we will pursue the consequences of it.

I should remark that we are not at all alone in taking this coincidence seriously. Of the 95 abstracts and 66 papers that were submitted to this session more than three quarters dealt with supersymmetric unified theories [13]. Also if you look at the hep-ph phenomenology bulletin board [14] you will notice that roughly a quarter of all papers that are submitted deal with SUSY So a Martian that just looks at the titles of hep-ph phenomenology might be confused as to whether SUSY has or has not been found.

Of course I do not have time to cover all the contributions to these proceedings [15,16,17] in detail but I will occasionally refer to some of the results that these people have reported.

My talk consists of three parts. First I will discuss the question of the weak mixing angle in SUSY Grand Unified Theories (GUTs) and in general the question of why SUSY GUTs were proposed and what are some of their virtues. Then I will discuss the top, how it fits in SUSY GUTs and how it may fit in the SM. Finally I will make some brief remarks about theories that attempt to

make statements about the masses and mixing angles of other quarks and leptons. I will not have time to review technicolor which has already been discussed in some detail by K. Lane [15].

2. WHY SUSY GUTs

Let me begin by reminding you very briefly why SUSY GUTs were proposed and what are some of their virtues. We begin with the fundamental premise that theorists believe in, that there is a fundamental scale in nature. This is near the gravitational scale, the Planck mass M_{Pl}, of the order 10^{18} GeV$/c^2$. An important question before even beginning to do physics is: can we discuss physics at our energies without knowing almost anything about the physics at this fundamental scale?

2.1. The Decoupling Hypothesis

The basic hypothesis that allows us to begin and go forward is the so called decoupling hypothesis. It says that the answer to the above question is yes. This hypothesis is very intuitive: it is the same reason for example that in cooking schools they don't teach you nuclear physics. It allows us to discuss large distance physics while being ignorant about what happens at short distances.

The quantitative statement of the decoupling hypothesis is that low energy physics parameters are fairly insensitive to the Planck mass or to this fundamental scale. They do not depend on positive powers of this scale, M_{Pl}^n, they are at most logarithmic functions of the Planck mass, $\log M_{PL}$.

Now the vast number of theories violate this decoupling hypothesis. The first class of such theories, which covers almost all theories, are the so-called non-renormalizable theories. These are maximally non-decoupled: in order to parameterize your ignorance of Planck scale physics you need infinitely many parameters all of which depend on positive powers of M_{Pl}. The second class of theories, like the SM, are the renormalizable theories. In these theories you can parameterize your ignorance of the fundamental physics with a few parameters, $\mathcal{O}(20)$, most of parameter, the Higgs mass (or scalar masses in general), which is actually very sensitively dependent on details of Planckian physics. Finally there are SUSY theories which are totally decoupled in the sense that all parameters depend at most logarithmically on M_{Pl}.

Now I should emphasize that this logarithmic dependence on M_{Pl} is actually very important. The weak mixing angle actually depends logarithmically on M_{Pl} and the experimental measurement that determines it is an indirect measurement of physics at the Planck scale (actually the unification scale).

The decoupling hypothesis was the original reason why SUSY GUTs were proposed. In order for SUSY to help you totally decouple low energy information from high energy uncertainties it is necessary that SUSY be realized at low energies near the weak scale. In particular there have to be SUSY partners for the ordinary particles, called superparticles or sparticles, with masses around the weak scale. The existence of these sparticles around the weak scale has significant consequences for the way coupling constants evolve as you go from low energies to high energies. As the coupling constant evolves, every time it encounters a superparticle the theory becomes less asymptotically free and therefore the coupling constant starts evolving more slowly. Therefore a generic feature of SUSY theories is that coupling constants, as you go from low to high energies, evolve more slowly which means that, if they have any tendency to meet they meet later than they would have met in a non-SUSY theory.

2.2. Coupling Constant Unification

This means that if the coupling constants are going to come together at all they are going to do so at a point which is later than a non-SUSY theory. This in turn implies that the fundamental scale at which coupling constants get unified is bigger so that the proton decay rate is slowed down. For similar reasons, having to do with the superparticle spectrum, the weak mixing angle changes.

In GUTs in general, and in SUSY ones in particular, the low energy coupling constants α_1 α_2 and α_3 are given in terms of just two fundamental parameters at high energies, namely the common coupling constant at the unification mass and the magnitude of the unification mass. Since three low energy parameters are given in terms of two, there is one prediction, which can be expressed in many ways. One possible fruitful way to express it is as a relation between $\sin^2 \theta_W$ and α_s at the mass of the Z^0 – that is, at low energies.

This relation was worked out many years ago both for non-SUSY [2] and SUSY theories [4,5], see figure 1. The data point is for the present measurement. The numbers shown (15, 16, 17 *etc.*) correspond to the logarithm of the energy at which unification occurs so that unification in SUSY theories occurs at $\approx 2 \times 10^{16}$ GeV. It can clearly be seen that the non-SUSY SM is excluded in view of the recent data relative to the SUSY SM. It may also be noted that in the non-SUSY model the unification mass is relatively small, around $10^{13} - 10^{14}$ GeV.

In 1981 a couple of conclusions were drawn: first, the value of $\sin^2 \theta_W$ for SUSY GUTs is bigger than for the non-SUSY theories; and second, because of the

Figure 1. The correlation in the values of $\sin^2\theta_W$ and $\alpha_s(M_Z)$ predicted in SUSY GUTs and ordinary GUTs. The bare superstring prediction is the point on the far right. The present 1994 are contrasted with the 1981 data. The bands are the uncertainties in the theoretical predictions of GUTs and SUSY GUTs. The numbers in the bands indicate the unification scale. The uncertainties in the theoretical predictions for superstrings are not known.

large magnitude of the unification mass, the proton is stable in paractice. It is interesting to recall the state of experimental affairs back in 1981. Just around the time this theory was constructed and reported in the Second Workshop on Grand Unification in Michigan (April, 1981) [18] there were reports of measurements of $\sin^2\theta_W$ and α_s. Of course the error bars were bigger but the central values of both $\sin^2\theta_W$ and α_s were in closer agreement with the non-SUSY case than the SUSY one. This was a very strong motivation for pursuing proton decay experiments; already at that conference candidate proton decay events were repoprted [19].

The following quote is from Marciano and Sirlin [20] and reflects the prevailing attitude about non-SUSY grand unification in April 1981.

> The basic idea of grand unification is very appealing. The simplest model based on $SU(5)$ has scored an important success in predicting a value of $\sin^2\hat\theta_W(M_W)$ which is in excellent agreement with recent experimental findings (after radiative corrections are included). It makes an additional dramatic prediction that the proton will decay with a lifetime in the range

$10^{30} \sim 10^{32}$ years. If correct, such decays will be seen by the planned experiments within the coming year (*or may already have been seen*)†. An incredible discovery may be awaiting us.

So in the beginning SUSY unification appeared to be dead even before it started; nevertheless as you know the data evolved. The fact that the discrepancy resolved itself in favour of the SUSY theory added an element of surprise to the history of SUSY unification and perhaps accounts in part for the great popularity of these ideas today.

2.3. Precision electroweak measurements

There are many tests that a theory must pass. One of the subjects that I will only briefly discuss is how SUSY does on precision electroweak data in terms of the well known $\epsilon_{1,2,3}$ parameters [21,22]. Roughly speaking ϵ_1 measures the breaking of up–down symmetry and ϵ_3 measures the breaking of $SU(2)\otimes U(1)$ or the number of $SU(2)\otimes U(1)$ breaking mass terms in the theory. Figure 2 shows the experimental data from the LEP

† My italics.

Figure 2. The 1σ error eclipses for ϵ_1 and ϵ_3 using only LEP and LEP plus SLC data. Also shown is the standard model prediction for different values of top and Higgs masses. This figure is taken from Altarelli [22].

Figure 3. The values of ϵ_1 and ϵ_3 in SUSY for a set of parameter values, the top mass is fixed at 174 GeV/c^2. This figure is taken from Altarelli [22].

Collaborations with and without the SLD data. The standard model gives a beautiful fit for a top mass of 170 GeV/c^2.

What happens when you add SUSY? Well SUSY of course has extra parameters which determine the masses of sparticles and each dot in figure 3 represent a different choice of SUSY parameters. As can be seen a class of SUSY theories lies within the preferred ellipse. Note that the ellipse is a 39% probability ellipse so that it is not the end of the world if you are not exactly within it;

plenty of SUSY theories are within one or two standard deviations. The moral is fairly straightforward: as long as you do not have extremely light sparticles SUSY can easily be consistent with the high precision electroweak data.

2.4. Flavour Changing Neutral Currents

The same holds true for flavour changing neutral currents, which typically place an extremely strong constraint on theories. This was an early difficulty for technicolor theories, wheras in SUSY it is possible to avoid it by having degeneracy between squarks as was postulated in the first SUSY GUT.

2.5. Sin $^2\theta_W$ Predictions

The next question I would like to turn to is, how unique is SUSY in making these predictions? In table 1 I try to compare non-SUSY unified theories with SUSY unified theories and strings that do not have unification below the string scale – truly single scale string theories. In GUTs, whether SUSY or not, you do not predict both α_s and $\sin^2\theta_W$, instead given one you predict the other. Looking at the number of standard deviations theory is from experiment, we see that in non-SUSY $SU(5)$ if you fit $\sin^2\theta_W$ and predict α_s it is off by quite a bit, but more to the point it gives a very low unification mass, just 8×10^{13} GeV/c^2, so that the proton would decay at a very rapid rate. Similarly if you take α_s from experiment and predict $\sin^2\theta_W$ you are off by quite a bit, and again you get a low unification mass 3×10^{14} GeV/c^2. SUSY GUTs work well, within one or two standard deviations, as you can see from the numbers.

The predictions that we quote for superstrings assume the minimal supersymmetric particle content up to the string scale M_s of about 4×10^{17} Gev/c^2 and do not include any potentially large string induced corrections†. These corrections are model dependent: in the absense of a model, it is not possible to estimate their magnitude. It is clear that the corrections would have to be quite large to make up for the large discrepancies with experiment. It is possible that a model will be found where the corrections are large and can be tuned to accomodate the data. Such a "fix" would be no better than accomodating ordinary $SU(5)$ with large corrections caused by random unobserved multiplets. Also to quote Barbieri *et al.* [23],

> Why should these corrections maintain the relations between the couplings characteristic of the grand unified symmetry, if such a symmmetry is not actually realized.

† Since the string scale is 20 times the SUSY GUT scale, the prediction for the proton mass is 20 GeV/c^2.

	Experiment	$SU(5)$	SUSY $SU(5)$	Bare Strings
$\alpha_s(M_Z)$	0.118 ± 0.007	0.07	$0.125 \pm .010$	0.20+?
		7σ	okay	11σ+?
$\sin^2\theta_W(M_Z)$	$.2317 \pm 0.0004$	0.2141	$0.2330 \pm .0025$	0.221+?
		44σ	okay	26σ+?

Table 1. The experimental values for $\sin^2\theta_W$ and $\alpha_s(M_Z)$ are contrasted with the predictions of three theories: ordinary GUTs, SUSY GUTs and bare superstrings. Under each prediction we list the number of standard deviations that it differs from experiment. GUTs and SUSY GUTs predict one of either $\sin^2\theta_W$ and $\alpha_s(M_Z)$; the other one is an input. For stings both $\sin^2\theta_W$ and $\alpha_s(M_Z)$ are predictions. The uncertainties in the theoretical predictions for superstrings are not known.

Figure 4. The top quark Yukawa coupling as a function of energy in the SM.

A simple possibility is that at M_s the string theory breaks to a SUSY GUT [23,24]; this is a promising new direction which may combine some of the virtues of both SUSY GUTs and strings. A challenge of such attempts would be to explain the ratio of the SUSY GUT to the string scale.

3. THE TOP QUARK

Finally the top quark has been announced [9]. It is the only quark that has a reasonable mass; you don't need any small parameter to understand its mass and at first sight if you did not know anything about the world you would have guessed that all of the quarks would have the same mass.

$$m_t \approx v \sim \sqrt{G_F} \quad \Longrightarrow \quad \lambda_t \approx 1 \qquad (1)$$

Of course this is not the case, other quarks have much smaller masses which means that they must have much smaller coupling constants, $\lambda \ll 1$, which requires symmetries. What I will now try to discuss is how nicely the top quark fits into SUSY; this is a qualitative virtue, not a quantitative virtue like the weak mixing angle.

3.1. Infrared Fixed points

A most interesting idea about computing the top quark mass first in the context of non-SUSY theories was discussed back around 1980 by Pendleton and Ross [25] and by Hill [26]. They point out that if the top Yukawa coupling (or top mass) is large enough, not too much smaller than unity, then a broad range of initial conditions will give rise to the same top quark mass, or Yukawa coupling, at low energy; see figure 4. This idea makes a prediction about the top quark: if you follow Pendleton and Ross this gives a top quark mass around 240-250 GeV/c^2 in the SM, which is fairly insensitive to initial conditions, and as a by-product you

also obtain an upper limit on the top quark mass. The reason for this behavior is a classic fixed point behavior in the equations which determine the evolution of the top quark and strong coupling.

$$16\pi^2 \frac{d\lambda_t}{dt} = \lambda_t(C_0\lambda_t^2 - C_3 g_3^2) \quad 16\pi^2 \frac{dg_3}{dt} = -b_3 g_3^3 \quad (2)$$

where C_0, C_3 and b_3 are constants whose values depend on the theories particle content.

$$\Longrightarrow 16\pi^2 \frac{d}{dt}\left(\frac{\lambda_t}{g_3}\right) = C_0\left[\lambda_t^2 - \frac{(C_3 - b_3)}{C_0}g_3^2\right] \qquad (3)$$

This equation shows that λ_t tracks g_3: if the top quark is too heavy then the Renormalization Group Equations (RGEs) push it down or if it is too small they increase it. This is a stable fixed point:

$$\left(\frac{\lambda_t}{g_3}\right)^2 \approx \frac{(C_3 - b_3)}{C_0} \quad \Longrightarrow \quad \frac{d}{dt}\left(\frac{\lambda_t}{g_3}\right) \approx 0 \qquad (4)$$

accounting for the behavior described above.

This is a nice idea which has been generalized to SUSY [27] and leads to interesting results. Of course in SUSY there are two Higgs fields, so what you obtain as a result of doing the same analysis is not exactly an absolute mass for the top quark but a scale for the top quark times the sine of an angle that measures the ratio of the vacuum expectation values of the two Higgses.

$$m_{top} = 190 \text{ GeV}/c^2 \times \sin\beta \qquad (5)$$

So the experimental range for m_t is consistent with the top being near its SUSY fixed point. This is helpful for bottom–tau unification [28]. That is, if you want to have the bottom and the tau masses equal at the grand scale, which occurs in many GUTs, then you have to be within 10% of the fixed point for the top quark mass [29]. So there is a nice connection between being at the fixed point and other ideas.

3.2. Upper Bounds on the Lightest Higgs Mass

Another thing which you gain by being at the fixed point is that you improve a great deal the upper limits on

Figure 5. The correlation between the top and lightest Higgs mass for $\alpha_s = 0.110 - 0.125$ (region between the dotted lines). Also shown is the upper bound on the Higgs mass in the minimal SUSY SM. This figure is taken from Barbieri *et al.* [30].

the Higgs mass that you have in SUSY theories; see figure 5. The solid line is the upper limit for the Higgs mass and is fairly model independent [30]. It depends logarithmically on the mass of the stop; as long as the stop is not much heavier than 1 TeV/c^2 this is a good upper limit. Now if you assume that you are near the top quark fixed point you obtain a much stronger upper limit given by the two dotted lines, the range depends on details like the precise value of α_s, but you can see for example that for $m_t = 170$ GeV/c^2 the upper limit goes down to about 90 GeV/c^2 from about 150 GeV^2. So if you are near the top fixed point this significantly pushes down the upper limit to the lightest Higgs mass.

3.3. Superparticle Spectra

Another virtue of being the top quark fixed point is that you have a reduction in the number of parameters that determine the spectrum of the superparticles. Instead of the usual set of parameters

$$m_{1/2}, \ m_0, \ B, \ \mu, \ \lambda_t, \ A \qquad (6)$$

you can compute the full superparticle spectrum in terms of two parameters and there are also some simplifications which emerge. For example the gauginos become $SU(2) \otimes U(1)$ eigenstates and you get simple mass relations

$$M_{\tilde{W}^{\pm}} \ = \ M_{\tilde{W}^0} = \frac{\alpha_2}{\alpha_1} M_{\tilde{B}} = 2M_{\tilde{B}} \qquad (7)$$

$$M_{\tilde{g}} \ \approx \ \frac{\alpha_3}{\alpha_1} M_{\tilde{B}} \qquad (8)$$

and in general the spectrum of superparticles becomes much more manageable [17,32]. *3.4 Dynamical Determination of the Top Yukawa Coupling* An interesting related idea is that of Kounnas, Zwirner and Pavel [32] and Binetruy, Dudas and Pillon [33] who give dynamical reasons why you might be near the top quark

fixed point. They argue that if there is a field that slides, for example a modulus field, on which the top Yukawa coupling depends and this is the only place where this field appears then minimizing the effective potential of that field:

$$\frac{\partial V_{eff}(\varphi)}{\partial \varphi} = 0 = \frac{\partial V}{\partial \lambda_t} \frac{\partial \lambda_t}{\partial \lambda_t^{GUT}} = 0 \qquad (9)$$

has a solution that corresponds to the fixed point.

$$\frac{\partial \lambda_t}{\partial \lambda_t^{GUT}} = 0 \qquad (10)$$

A solution which says that the low energy top Yukawa coupling is insensitive to its grand unified value. They also argue that this fixed point solution may be the lowest minimum of this potential and this may give, in such theories, a dynamical reason for being near the fixed point. These authors are pursuing these ideas further and are trying to argue about the smallness of the bottom with respect to the top Yukawa coupling to explain the lightness of the bottom quark mass.

3.4. Vacuum Stability in the Standard Model

So far we have shown that in SUSY theories we get an upper bound on the lightest Higgs, what happens in the non-SUSY theories – in the SM? Actually in the SM you get a lower bound on the mass of the Higgs and this happens because of vacuum stability. If λ is the quartic coupling of the Higgs field which is responsible for the mass of the Higgs then of course λ has to be positive to have a stable Hamiltonian which is not unbounded from below [34,35]. However if you have a large top Yukawa coupling the RGEs for the Higgs mass (or the quartic coupling) have a positive term and a negative term where the negative term depends on the fourth power of the top Yukawa coupling.

$$\frac{d\lambda}{dt} = \lambda^2 - \lambda_t^4 \qquad (11)$$

So if the top Yukawa coupling is large, which of course it must be for the top to be heavy, then you are potentially driven to a negative λ and an unstable situation. To prevent this instability you have to have a large quartic coupling which means a lower limit on the Higgs mass. This lower limit can be computed and is shown in figure 6. It is not very sensitive to the top mass. The scale Λ in the standard, non-SUSY model is the scale at which new physics must enter, namely the scale at which the vacuum destabilizes. So if you want to have a stable vacuum up to the GUT mass or up to the Planck mass there is a lower limit to the higgs mass $\mathcal{O}(135)$ GeV/c^2. To summarize in the SM you get a lower limit to the Higgs mass if the SM is valid all the way up to the GUT scale and in the SUSY SM you get an upper limit.

Figure 6. The lower limit on the Higgs mass as a function of the unification scale Λ for $m_t = 174$ GeV/c^2. This figure is taken from Altarelli *et al.* [35].

4. OTHER QUARK AND LEPTON MASSES

So far we have focussed on just two parameters the weak mixing angle and the top mass. Of course the theory has many more parameters: the SUSY theory has another 20 parameters about which have not said anything. 14 of these parameters have to do with the quark masses and mixing angles. When theorists try to attack this problem they have to confront a big disadvantage relative to the experimentalists. The experimentalist have only 14 $(6+3+3+1+1)$ parameters to measure, the theorists *a priori* has three 3×3 matrices each element of which is a complex number. Therefore the theorist starts out with 54 $(= 3 \times 3 \times 3 \times 3 \times 2)$ parameters and wants to explain some of these fourteen.

The idea of grand unification is a great help in reducing the number of parameters. GUTs can relate the lepton masses to the down and up masses, as well as neutrino masses, and in $SO(10)$ GUTs all of these mass matrices are related to each other. Therefore it suffices to focus on one of these mass matrices, say the electron or negatively charged lepton mass matrix to explain the rest. Now the number of free parameters has been reduced to one 3×3 matrix which after removing some phases leaves 16 parameters. Since 16 is larger than 14 so you have still not quite begun to predict something of relevance for experiment.

In order to ameliorate this situation it is clear what we have to do. Grand unified gauge symmetry is not sufficient to make predictions you need some more symmetry you need some flavour symmetry that will relate quarks of different families to each other and can perhaps explain why all quarks and leptons are not degenerate with the top quark right at the weak scale.

4.1. The Textural Approach

There are at least two approaches to the problem of fermion masses and several people have done interesting work on this. First there is what is called the textural approach. Texture refers to the following: you start with every mass matrix, quark or lepton, as a 3×3 matrix. Since you have to make assumptions to reduce the number of parameters you can assume a specific pattern of zeros and symmetry or antisymmetry of this matrix to reduce the number of parameters. Some people object that postulating a number to be zero is choosing it to be a very specific value. The great thing about zero is that zero can be the consequence of a symmetry. We can think of many ways to make something zero; that is the motivation for choosing zeros as opposed to any other number for specific entries. There are also regularities like nearest neighbour mixing *etc.* in the pattern of observed mixing angles that also phenomenologically motivate some zeros. This approach was pioneered by Fritsch [36] and in the context of GUTs by Georgi and Jarlskog [37]. A lot of work which has been done in the last few years along these lines [38].

4.2. The Operator Approach

Then there is a more ambitious approach which you may call the operator approach. According to this approach you start with first of all a SUSY $SO(10)$ theory: SUSY to explain the weak mixing angle and $SO(10)$ to be able to relate all quarks and leptons to each other. You right down the smallest set of operators that you can that will give masses to all the quarks and leptons. This approach has been pursued recently [39] and it has some quantitative virtues. Its biggest virtue is that it is very predictive with 6 inputs it can get 14 outputs, namely the parameters of the quark and lepton mass matrix, thereby making 8 predictions.

I do not have space to discuss the whole technology that is involved in this approach, it is a very technical subject. There is a discrete scanning procedure that gives you a discrete set of theories of which three or four survive this test. Table 2 shows an example of the type of inputs and outputs that are obtained. If you input the six number in the first column, which are very well known, you output 8 numbers. In addition you predict very precisely things having to do with CP violation [40]:

$$\sin 2\alpha = -.46 \tag{12}$$
$$\sin 2\beta = -.49 \tag{13}$$
$$\sin 2\gamma = -.84 \tag{14}$$
$$J = +2.6 \times 10^{-5} \tag{15}$$

These predictions are sufficiently sharp that they can be tested in the B- factory for example.

Input Quantity	Input Value	Predicted Quantity	Predicted Value
$m_b(m_b)$	4.35 GeV	m_t	176 GeV
$m_\tau(m_tau)$	1.777 GeV	$\tan\beta$	55
$m_c(m_c)$	1.22 GeV	V_{cb}	.048
m_μ	105.6 GeV	V_{ub}/V_{cb}	.059
m_e	.522 MeV	m_s(1 GeV)	172 MeV
V_{us}	.221	$\hat{B}_K$	.64
		m_u/m_d	.64
		m_s/m_d	24.

Table 2. Predictions of a class of models from [39].

5. CONCLUSIONS

To conclude I would like to state some of my personal biases which are actually shared by many people. These biases are of course not time independent†

The first bias is a quantitative one namely that SUSY GUTs are correct on the basis of the evidence we have for the weak mixing angle. As I have said this could be a 2 in 100 accident and in that case we have nothing to go by. Then there are some qualitative virtues of SUSY GUTs, of these I have discussed:

- Naturalness: the light sector decouples from the heavy sectors of the theory. The decoupling is not total the weak mixing angle still depends logarithmically on M_{PL}.
- The non-observation of proton decay; this is only a qualitative virtue since any theory which does not unify shares it.
- The fact that the top quark fixed point fits nicely within SUSY.

Also other virtues that are consistent with having a heavy top quark, that I did not have space to discuss, also fit nicely in the context of SUSY.

- Bottom–tau unification.
- Radiative electroweak symmetry breaking [41].

Of course the big question is how shall we know if SUSY is really there? and when. The easy answer is when LHC and NLC are built. In order to have decoupling of the weak world from the Planckian world we need SUSY particles to exist around a TeV or below. Or course this is not a hard number it is an estimate. The first consequence of SUSY is that all sparticle masses are roughly less than 1 Tev. Before LHC and NLC there is still hope that we may see something for example proton decay.

Proton Decay [17,42] SUSY predicts that the proton can decay at a reduced rate into kaons.

$$p \to K^+ + \bar{\nu} \qquad n \to K^0 + \bar{\nu} \qquad (16)$$

† As of 4:04 p.m. July 25th, 1994.

These are very unique modes; they are general consequences of SUSY theories under very general conditions. The strongest ingredient is Fermi statistics so it is not a highly model dependent statement that nucleons decay into kaons. Icarus and Superkamiokande may get lucky and with limits $\mathcal{O}(10^{34})$ years may be able to see such events. I should say that in contrast to non-SUSY theories SUSY does not make a sharp prediction about the proton lifetime because proton decay is mediated by very heavy Higgs-like particles (not gauge particles) whose coupling constants are not very well under control, so this is not a hard prediction.

Neutron and electron electric dipole moments (edm). If you take a SUSY theory with sparticles around 100 GeV/c^2 and phases of order unity you find that the edm of the neutron is 10^{-23} ecm which is a factor of 100 too large. This is not a deadly diseases because we do not know the masses of sparticle or their phases. However it suggests that if the limits for edms improve by a factor of 10 or 100 then there is a good chance if SUSY is right that something may be seen and actually if nothing is seen it is reason to start wondering about SUSY.

Flavour surprises There are many possibilities for these because to ensure that there are no FCNC you have to assume degeneracy in sparticle masses which is broken by weak effects. Therefore flavour surprises in SUSY theories are possible and the B-factory, for example, may be a place to look for these things or for anything that has to do with theories that predict CKM elements and fermion masses.

Neutrino masses I really do not have any idea what to say about neutrino masses. To make any statement you have to make a long list of assumptions that one does not have very strong faith in. Chorus, Nomad and hopefully the long baseline experiments will be able to resolve this. Lots of SUSY GUTs have:

$$\mu \to e\gamma \qquad (17)$$

The only hint for perhaps some physics beyond the SM is the weak mixing angle. To predict it you need to simultaneously postulate unification of the couplings constants with an $SU(3) \otimes SU(2) \otimes U(1)$ desert and low energy SUSY, namely particles at accessible energies. The weak mixing angle depends on the integrated effects of virtual SUSY that extend from the Planck mass all the way down to the weak scale. So if SUSY turns out to be right it will be fascinating that the virtual effects of the superparticles that propagate information down

from the Planck mass to the weak scale will have been seen before the actual live superparticles themselves.

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QUESTIONS *A.V. Efremov, JINR–Dubna:*

In Vysotsky's talk (these proceedings) we heard about one more indication of supersymmetry connected with b-quark decay. Do you consider it to be important also?

S. Dimopoulos:

I think it is an interesting result. I would not go so far as to call it another indication for SUSY; not yet.

J.L. Chkareuli, IoP–Tiblisi/Sussex:

I have a little comment concerning the unification of the standard coupling constants. Actually, it is not a privilege of the SUSY $SU(5)$ model only. We found many Extended GUTs from $SU(6)$ giving a perfect unification in the non-SUSY case. All these EGUTs containing a number of additional pairs of conjugated multiplets in their fermion spectrum are proved to be broken not through the standard $SU(5)$ but through alternative channels. Besides the minimal $SU(6)$ case there are good examples of natural unification in $SU(9)$ (Frampton) and $SU(11)$ (Georgi) models including the gauged quark lepton families.

S. Dimopoulos:

you are refering to theories with intermediate scales. If you have intermediate scales you do not predict $\sin^2 \theta_W$, $\sin^2 \theta_W$ is an input and then you predict some phenomena at some scale $\mathcal{O}(10^{10})$ GeV. So this is not an experimentally testable success.

G.G. Ross, Oxford:

I should like to point out that M_{string} is not the unification scale in an arbitrary string theory – it must be determined for the specific string theory. In the absence of this information you must use M_X as a free parameter – just as in SUSY GUTS.

S. Dimopoulos:

Indeed if you succeed in constructing a string theory that breaks at $M_s = 4 \times 10^{17}$ GeV/c^2 down to a SUSY GUT (with the usual SUSY GUT scale of $M_X = 2 \times 10^{16}$ GeV/c^2) you will have succeeded in combining the virtues of SUSY GUTs with those of strings. This is precisely the program of Ibanez *et al.* and Lykken *et al.* that I refered to in my talk. As I explained in my talk the predictions that I quoted for "bare" superstrings are what you get if you the minimal supersymmetric particle content up to M_s, no intervening unification and no large threshold corrections to fix things up.

G. Crosetti, INFN–Genova:

How robust is the upper limit on the Higgs masses? Because if it is really very strong LEP-II can state something on the SUSY model in the next few years. Do you agree with this?

S. Dimopoulos:

It depends logarithmically on the assumed sparticle masses.

H. Haber, UCSC

It also relies on you having $\tan \beta$ rather small which is why the limit is so strong.

S. Dimopoulos:

I recall the upper limit to be 160 GeV/c^2 (even if sparticles are at 10 TeV/c^2) for any value of $\tan \beta$ up to ~ 60. On my transparency I showed what happens up to $\tan \beta = 10$ because the upper limit does not change much for $\tan \beta > 10$

H.B. Nielson, NBI

I would like to mention our work on trying to predict the fine structure constants.

S. Dimopoulos:

If I recall correctly your predictions have an uncertainty of $\sim \pm 20\%$. The experimental accuracy on $\sin^2 \theta_W$ is $\pm 0.2\%$. Ordinary GUTs are off by only $\sim 10\%$ on $\sin^2 \theta_W$, yet this means 40 standard deviations. It is hard to draw a conclusion until you improve the accuracy of your calculations.

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